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METALLURGICAL AND GEOMETRICAL FACTORS AFFECTING ELEVATED-TEMPERATURE TENSILE PROPERTIES OF DISCONTINUOUS-FIBER COMPOSITES

by Donald W. Petrasek, Robert A. Signorelli, and John W. Weeton

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ERRATA

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March 1967

Page 8, paragraph 3: Lines 6 and 7 should read "measured to be between 3° and 5°. The fiber orientation of each specimen that had a tensile-shear failure varied from parallel to the tensile axis to those misalined by 3° from the".

Page 12, paragraph 2, line 12: Delete "result".

Page 14, paragraph 3, line 5: Change "misalinement" to "misalined".

Page 15: Replace with the attached page.

Page 16: Line 13 should read "percent fiber content. The ratio of the shear strength of the matrix to the tensile strength of the composite is lowered with".

Page 21, line 2 from the bottom: Reference 1 should be reference 10.

Pages 23, 24; equations (A1), (A3): The quantity $\left(\frac{1 - L_c}{2L}\right)$ should be $\left(1 - \frac{L_c}{2L}\right)$.

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METALLURGICAL AND GEOMETRICAL FACTORS AFFECTING ELEVATED-TEMPERATURE TENSILE PROPERTIES OF DISCONTINUOUS-FIBER COMPOSITES

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SUMMARY

The length-diameter ratio and the orientation of the fibers in discontinuous-fiber-reinforced composites were correlated to their elevated-temperature tensile properties. The composites were made of copper and a copper - 2 percent-chromium alloy reinforced with tungsten fibers having various length-diameter ratios. These composites were tested in tension at 300°, 900°, and 1500° F, and the results were then compared with continuous-length-fiber-reinforced composites containing the same matrix materials and fiber contents.

The fiber orientation in the composite was extremely critical at elevated temperatures. Shear failures occurred at 1500° F for specimens in which the fibers were misalined from the tensile axis by as little as 3°. Also, composites which failed in shear had significantly lower tensile strengths than did composites having fibers alined parallel to the tensile axis of the specimen.

Tensile strengths of discontinuous-fiber-reinforced composites in which the fibers were alined parallel to the tensile axis were dependent upon the length-diameter ratio of the fibers in the composite. As the length-diameter ratio of the reinforcing fibers decreased, the tensile strengths of the composites decreased.

Alloying the copper matrix with chromium increased the matrix shear strength, which was beneficial even though the alloying element reacted with the fiber. Since load transfer from the matrix to the fiber was dependent upon the shear strength of the matrix, the greater the shear strength, the higher the load transfer capabilities of the matrix. Thus, the tensile strength of composites with a copper - 2 percent-chromium matrix was higher than that of unalloyed-copper-matrix composites having the same fiber content and the same length-diameter-ratio fibers.

INTRODUCTION

There is a growing interest in the use of filaments, short-length wire and whiskers, for the strengthening of ceramics and metals; as a result, a sizable research effort is being directed towards the development of fiber composites.

An understanding of composite strengthening mechanisms is equally as important to furthering the fiber composite field as the development of products of interest. For this reason, the room-temperature and elevated-temperature tensile behavior of model-system composites of copper and copper alloys reinforced with tungsten fibers was studied at the NASA Lewis Research Center (refs. 1 to 3). The results showed that the room-temperature and elevated-temperature tensile properties of the composites were proportional to the fiber content present in the composite and that a law of mixtures relations was obeyed. Room-temperature tensile properties were also determined for discontinuous-tungsten-fiber-reinforced copper-matrix composites. The room-temperature tensile properties obtained, along with the length of fibers used, were similar to those obtained for continuous-length-fiber-reinforced composites. A logical extension of this work was to determine the elevated-temperature tensile properties of discontinuous-tungsten-fiber-reinforced copper and copper-alloy composites.

Both analytical and experimental investigations were conducted on composites containing discontinuous fibers (refs. 1 and 4 to 9). A number of similar equations were derived and proposed that relate the composite tensile strength to the ratio of length to diameter of the fibers used (refs. 1, 4, 6, and 7). The equations predict that the tensile strength of a discontinuous-fiber-reinforced composite should increase with increasing fiber length-diameter ratio. From the previously mentioned references, tensile data obtained at room temperature with the use of mutually insoluble components qualitatively substantiate the validity of these equations. However, limited data exist for verification of these equations with the use of soluble components and for both soluble and insoluble systems at elevated temperatures. Other factors such as fiber overlap and fiber orientation were explored less thoroughly, and these factors are critical at elevated temperatures.

In view of the preceding discussion, additional studies of discontinuous-fiber - metal composites at elevated temperatures were warranted. The objective of this investigation was to correlate variations of fiber length-diameter ratio and orientation to the tensile behavior of discontinuous-fiber-reinforced composites from 300° to 1500° F. Composites consisting of a matrix of copper or copper - 2-atomic-percent-chromium alloy, reinforced with 0.005-inch-diameter tungsten fibers having various length-diameter ratios, were studied. Selecting copper or a copper - 2-percent-chromium alloy as the matrix material permitted comparison of the results with those reported from previous work on the elevated-temperature tensile properties of composites containing these materials reinforced with continuous-length tungsten fibers. Although unalloyed copper is insoluble

in tungsten, the chromium in the copper-chromium alloy is soluble in tungsten; it reacts with the fiber, and slightly reduces the tensile strength (ref. 3). The chromium addition to copper, however, increases the shear strength of the material relative to that of unalloyed copper. Thus, the effect on the load transfer efficiency of increasing the shear strength of the copper by the addition of chromium can be determined.

The composites were tested in tension at 300°, 900°, and 1500° F. Results were compared with those obtained for continuous-length-fiber-reinforced composites containing the same matrix and fiber content.

MATERIALS, APPARATUS, AND PROCEDURE

Materials

For the composites studied in this investigation, the reinforcing fiber was commercially pure 0.005-inch-diameter tungsten wire; the insoluble matrix material was high-purity copper (99.99 percent); and the soluble matrix material was a copper alloy containing 2 atomic percent chromium. The elevated-temperature tensile properties of tungsten-fiber-reinforced composites, consisting of the matrix material and continuous-length tungsten fibers, were determined in a previous investigation (ref. 3); therefore, the tensile properties of discontinuous composites could be compared to those of continuous-fiber-reinforced composites.

Specimen Preparation

Tungsten wires 1, 1/2, or 1/4 inch in length (having length-diameter ratios of 200, 100, or 50, respectively) were inserted into 1/8-inch-inside-diameter - closed-end quartz tubes. A piece of the infiltrant was placed in the tube above the fibers. The entire assembly was then heated to 2200° F and held at that temperature for 1 hour in a vacuum atmosphere. The transparency of the quartz tube permitted the observation of fiber distribution, overlap, and orientation. Specimens that had large numbers of fiber ends in a cross section, with either an insufficient overlap or an excessive misalinement, were discarded before infiltration. The misalinement of the fibers with the tensile axis of the specimen varied with the length of the fiber. For example, if it was assumed that no bending would take place, the maximum misalinement for 1/4-inch fibers would be 30°; for 1/2-inch fibers, $14\frac{1}{2}^{\circ}$; and for 1-inch fibers, 7°. Specimens that had adequate overlap and alinement were infiltrated. Fiber orientation was determined after tensile testing by metallographic examination at and near the fractured portion of the specimen.

After infiltration, the rods were ground into button-head tensile specimens that were approximately 4 inches long. Specimens consisting of either 1/4- or 1/2-inch-long fibers had a test section, or gage length, of 1 inch; and specimens having 1-inch-long fibers had a gage length of 1.5 inches. The fiber content ranged from 20 to 50 volume percent.

Test Procedure

Elevated-temperature tensile tests on the composites were made by using an Instron tensile testing machine. The elevated temperatures selected for the investigation were 300°, 900°, and 1500° F, and a constant cross-head speed of 0.10 inch per minute was used for all tests. The specimens were tested in a vacuum capsule at a pressure of less than 1×10^{-3} torr to inhibit oxidation of the composites.

The cross-sectional area and the volume-percent fiber content for all composite specimens were obtained by sectioning the specimen transversly in an area immediately adjacent to the fracture. The sections were mounted, polished, and photographed at a magnification of 50. A wire count was obtained from the photographs, and the cross-sectional area and volume-percent fiber contents were calculated. The fibers were assumed to be distributed randomly throughout the composite and that the volume fraction of fiber was equal in any given cross section.

Failure Analysis

On a sterographic microscope the fracture edges of the discontinuous composite specimens were examined for fiber necking, fiber overlap, fiber pull out, and shear at the matrix-fiber interface. Fiber orientation was determined from optical measurements made at a magnification of 250 on mounted fracture edges of specimens. The variation of fiber-alinement data was correlated with tensile-strength variations and fracture behavior.

Microstructural Studies

Metallographic studies were made of the cross section of the tungsten-fiber-reinforced copper and copper-alloy composites. All the specimens were swab etched with Murakami's etchant (10 grams potassium hydroxide, 10 grams potassium ferricyanide, and 100 cc of water) to reveal the structure of the tungsten wires and the reaction zone at the matrix-fiber interface. Photomicrographs were then taken at magnifications of 750 and 250.

TABLE I. - TENSILE STRENGTH OF DISCONTINUOUS-TUNGSTEN-FIBER-REINFORCED COPPER COMPOSITES

Fiber length, in.	Aspect ratio	Test temperature, $^{\circ}F$	Specimen	Tensile strength, psi	Fiber content, vol. %	Type of failure, (a)
0.5	100	300	1	83 400	32.3	T
			2	83 100	32.9	
			3	91 100	33.1	
			4	91 600	34.6	
		900	1	54 500	27.4	T
			2	48 200	30.1	
			3	54 800	32.9	
			4	65 500	33.1	
			5	75 400	34.1	
			6	66 800	34.3	
			7	58 000	34.4	
			8	65 800	35.0	
			9	66 700	36.7	
			10	72 800	38.0	
		1500	1	15 000	22.1	S
			2	27 800	24.2	T
			3	22 500	28.1	S
			4	20 000	31.8	S
			5	30 700	32.0	T
			6	36 400	32.0	T
			7	32 500	32.3	T
			8	17 700	34.3	S
			9	33 800	36.9	T-S
			10	37 200	36.9	T
			11	18 900	37.1	S
			12	28 100	39.0	T-S
			13	33 300	39.2	T-S
			14	16 900	39.7	S
			15	23 600	43.3	S
1.0	200	900	1	78 000	34.2	T
			2	97 500	42.1	
			3	98 000	47.6	
			4	94 400	49.6	
			5	103 500	50.9	
			6	95 300	51.4	
		1500	1	50 700	36.6	T
			2	46 300	34.6	
			3	59 800	38.3	
			4	54 100	39.6	
			5	52 000	40.0	
			6	59 300	44.8	
			7	57 200	45.4	
			8	65 800	45.8	
			9	66 300	47.2	
			10	67 600	48.6	
			11	71 500	50.5	

[a]S, shear; T, tension; T-S, tensile-shear.

Measurements of the depth of visible penetration, or alloying of the copper alloy binder with the tungsten fibers, were made on etched cross sections of the composite at a magnification of 750 with a Filar eyepiece.

RESULTS

Tensile Results

The tensile strength results are shown in tables I and II and are plotted in figures 1 and 2. The solid curve on each plot represents the relation of tensile strength to fiber content obtained for continuous-length-fiber-reinforced composites as reported in reference 3. The data points plotted are for discontinuous-length-fiber-reinforced composites which were investigated in this study. The dashed curve represents the relation between composite tensile strength and fiber content and the expected matrix strength contribution for those specimens which failed in tension, as noted in tables I and II. Figures 1 and 2 show that, with the exception of the results at 1500° F, the data fall close to the appropriate dashed curve. Those data points at 1500° F which do not fall on or near the dashed curve indicate specimens for which shear failures occurred on a plane on which the fibers were oriented. Further, shear failures occurred only for those composite specimens containing fibers oriented at an angle to the tensile axis. There was a greater tendency for

TABLE II. - TENSILE STRENGTH OF DISCONTINUOUS

TUNGSTEN-FIBER-REINFORCED COPPER -

2-PERCENT-CHROMIUM COMPOSITES

Fiber length, in.	Aspect ratio	Test temperature, ^{o}F	Specimen	Tensile strength, psi	Fiber content, vol. %	Type of failure, (a)
0.25	50	1500	1	17 500	23.5	S
			2	23 500	42.3	S
0.5	100	300	1	87 500	31.1	T
			2	91 200	32.7	
			3	109 000	38.6	
			4	107 000	41.1	
			5	107 000	41.9	
		900	1	80 500	36.3	T
			2	84 500	37.4	
			3	83 200	38.3	
			4	84 000	38.3	
			5	70 200	38.5	
			6	84 500	40.2	
			7	89 800	44.3	
			8	84 400	46.0	
		1500	1	28 300	25.6	T-S
			2	34 300	33.5	
			3	38 500	33.5	
			4	34 300	33.6	
			5	35 900	34.5	S
			6	36 000	36.2	T-S
			7	33 300	36.3	
			8	35 100	37.3	
			9	43 000	38.0	
			10	37 700	40.3	
			11	30 400	42.7	
			12	40 000	48.0	S
			13	29 200	48.1	S
1.0	200	1500	1	46 300	35.8	T-S
			2	54 100	37.2	T
			3	68 900	42.6	T
			4	60 800	47.8	T-S

[a]S, shear; T, tensile; T-S, tensile-shear.

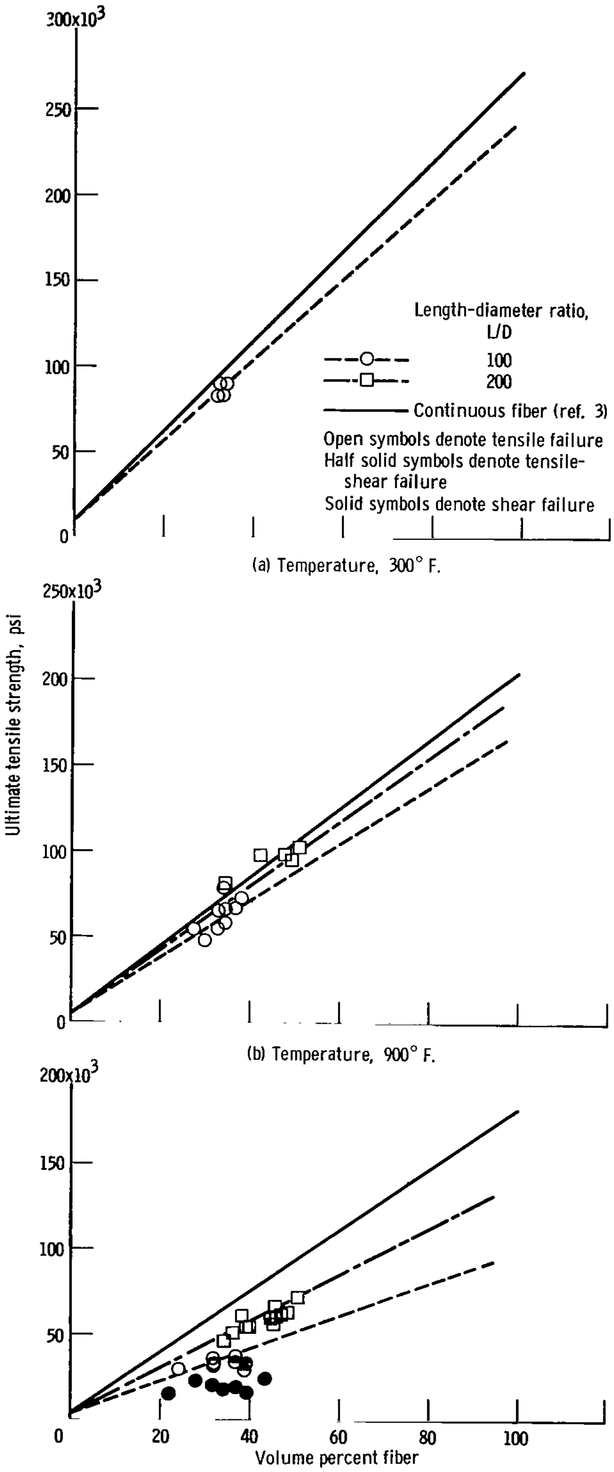


Figure 1. - Tensile strength as function of fiber content for discontinuous-tungsten-fiber-reinforced copper composites.

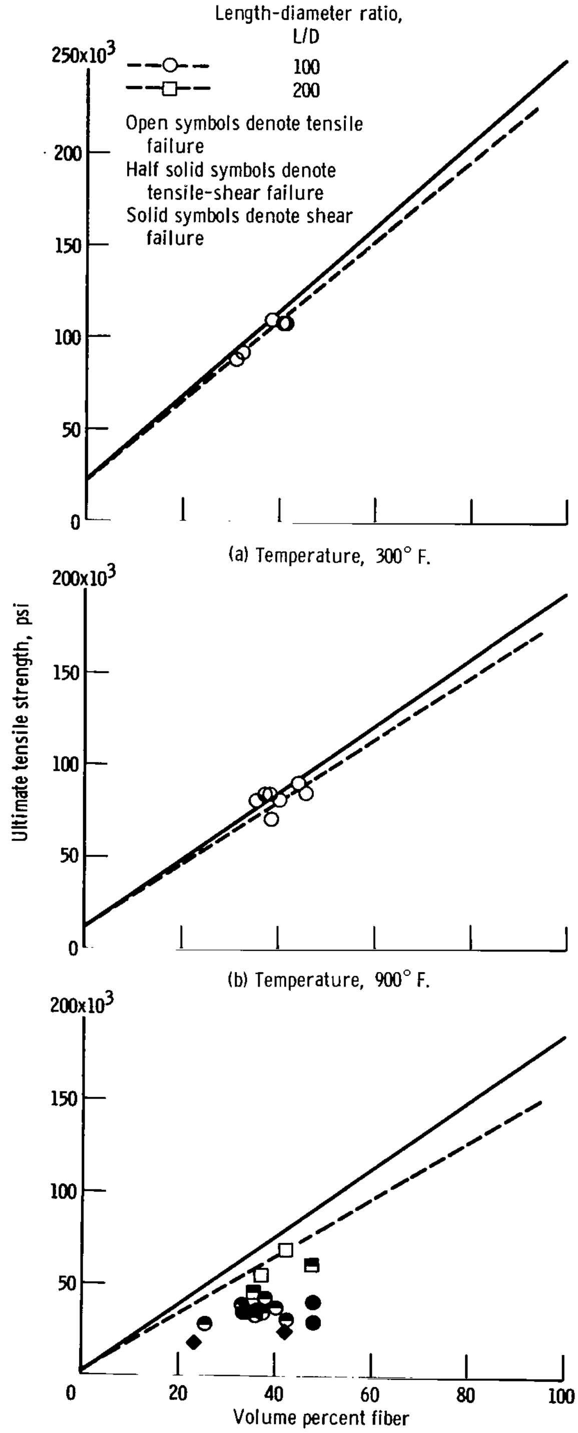


Figure 2. - Tensile strength as function of fiber content for discontinuous-tungsten-fiber-reinforced - copper - 2-percent-chromium composites.

fibers to be misalined in specimens containing fibers having lower length-diameter ratios.

At all the test temperatures investigated, discontinuous-length-fiber-reinforced composites are weaker than continuous-length-fiber-reinforced composites of equal volume percent fiber content. Also, the composite tensile strength decreases with the decreasing length-diameter ratio of the reinforcing fibers. For example, composites containing fibers with a length-diameter ratio of 200 are stronger than composites with the same fiber content but with fibers having a length-diameter ratio of 100. Also evident from figures 1 and 2 is that, as the testing temperature is increased, composites containing fibers having a length-diameter ratio of 100 deviate increasingly from the strength obtained by using continuous-length fibers. The copper - 2-percent-chromium composites that failed in tension more nearly approach the tensile strength of the continuous-length-fiber-reinforced composites than do copper composites having fibers with the same length-diameter ratio.

Failure Analysis

Examination of the fracture edges of the specimens tested in tension revealed three types of failure: tensile, shear, and a combination of both, tensile-shear. The type of failure that occurred for each specimen is listed in tables I and II and is indicated in figures 1 and 2. Necking of the majority of the fibers occurred in those specimens that had tensile failures. Some necking of the fibers was observed in specimens failed by tensile-shear, while there was no necking of the fibers in those specimens failing in shear.

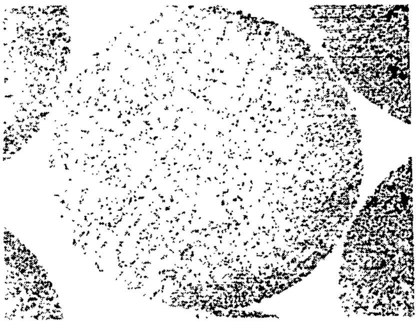
The specimens having tensile-shear or shear failures contained fibers that were misalined from the tensile axis, whereas specimens having tensile failures had fibers that were alined parallel to the tensile axis. In shear failures that occurred on a plane parallel to the fiber orientation, the plane was misalined from that of the tensile axis. The angle at which the fibers were misalined from the tensile axis of the specimens was measured to be between 3° and 5°. The fiber orientations of specimens that had tensile

See errata

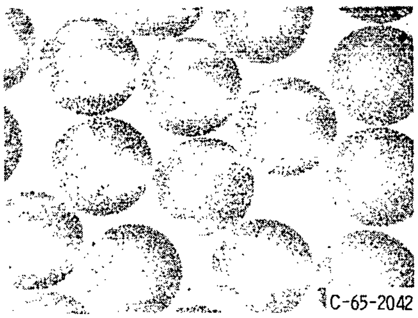
shear failures varied by 3° from parallel to the tensile axis to those misalined from the tensile axis. Specimens that had tensile failures contained fibers alined within 2° of the tensile axis.

Microstructural Studies

Tungsten-fiber - copper composites. - The microstructure of a cross section of a tungsten-fiber - pure-copper composite is shown in figure 3. Alloying between the fiber

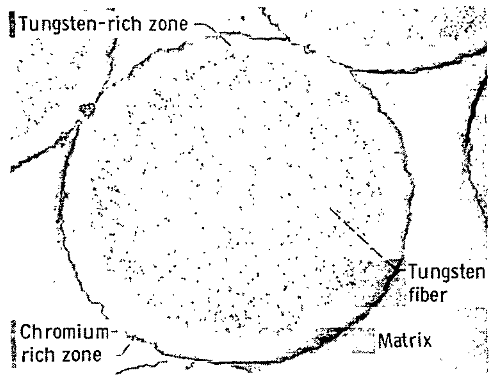


(a) Magnification, 750.

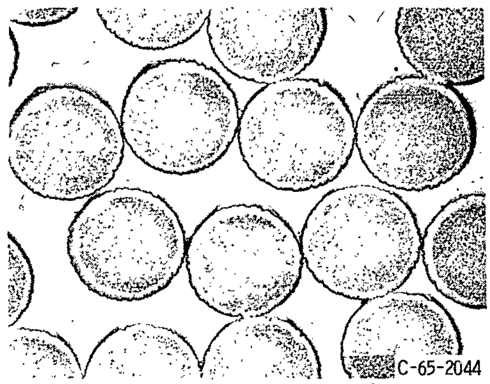


(b) Magnification, 250.

Figure 3. - Pure-copper - tungsten-fiber-reinforced composite. (Reduced 50 percent in printing.)



(a) Magnification, 750.



(b) Magnification, 250.

Figure 4. - Copper - 2-percent-chromium - tungsten-fiber-reinforced composite. (Reduced 50 percent in printing).

and matrix did not occur, as would be expected since tungsten and copper are mutually insoluble.

Tungsten-fiber - 2-percent-chromium composites. - Figure 4 shows a cross-sectional view of a typical copper - 2-percent-chromium composite. Two phases are formed at the periphery of the fiber: a single-phase tungsten-rich structure and a thin platelike chromium-rich phase (white zone at the edge). Penetration measurements generally revealed an increase in the diameter of the fiber because of the alloying reaction, as was also observed earlier in reference 3. The width of the alloyed fiber zone varied from approximately 0.0001 to 0.0006 inch. The initial diameter of the fiber varied by 0.00003 inch from a total diameter of 0.005 inch. These values also agree with those obtained in reference 3.

DISCUSSION

The results indicated that the orientation of the fibers in the composite was the most

significant factor in achieving high tensile strength at elevated temperatures for discontinuous-fiber-reinforced composites. Composites having fibers alined parallel to the tensile axis of the specimen had significantly higher tensile strengths than composites having fibers misalined as little as 3° from the tensile axis. It should also be noted, from tables I and II and from figures 1 and 2, that shear failures due to misalined fibers occurred only at test temperatures of 1500° F and that the number of misalined fiber specimens was less for those specimens with a greater fiber length-diameter ratio.

The tensile strength of discontinuous-fiber-reinforced composites containing alined fibers was dependent upon the length-diameter ratio of the fibers in the composite. As the length-diameter ratio of the reinforcing fibers decreased, the tensile strength of the composite decreased. The decrease in tensile strength as a function of length-diameter ratio increased with increasing test temperatures. Also, in comparison with the unalloyed copper matrix composites, the composites of copper-chromium containing alined fibers had lower decreases in strength with decreasing length-diameter ratio fibers, relative to continuous-length-fiber reinforced composites. Copper-chromium composites that had the same fiber length-diameter ratio as unalloyed-copper-matrix composites more nearly approached the tensile strengths obtained by using continuous-length fibers.

The tensile strengths of discontinuous-fiber-reinforced composites are compared in figure 5 with those obtained by using continuous-length fibers (ref. 3) as a function of test temperature. Copper composites containing continuous-length fibers are slightly stronger than copper-chromium composites containing continuous-length fibers. As reported in reference 3, the copper-chromium alloy reacted with the fiber, and the result was slightly lower fiber strength. In contrast, the comparison for discontinuous-fiber-reinforced composites reveals that the copper-chromium composites are stronger than the unalloyed-copper-matrix composites. The chromium addition to copper increases the shear strength of the matrix. Load transfer from the matrix to the fibers

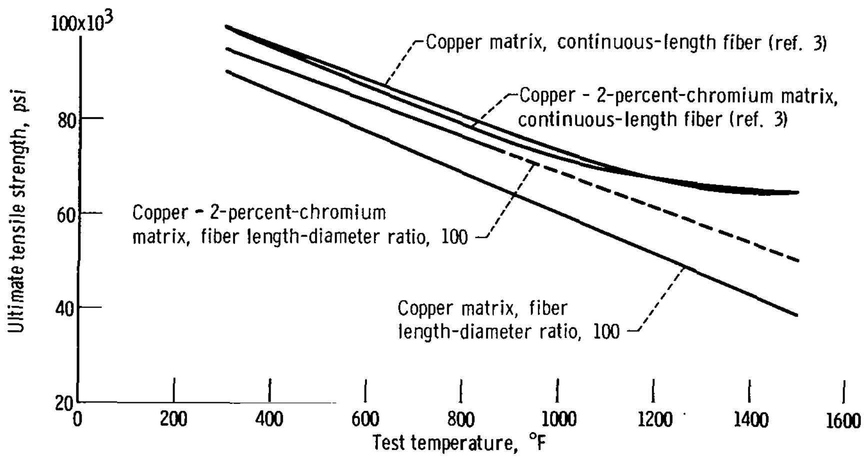


Figure 5. - Composite tensile strength for composites containing 35 volume percent fibers as function of test temperature.

in a discontinuous-fiber-reinforced composite is dependent upon the shear strength of the matrix, as will be discussed in more detail later in this report. Higher composite tensile strength results by using the copper alloy because of its ability to transfer greater loads (when the length-diameter ratio of the fibers is the same). It is significant that the increase in composite strength due to the higher shear strength of the copper alloy is greater than the decrease in composite strength due to the alloying reaction with the fibers and the subsequent decrease in fiber strength. Thus, the results show that alloying can be beneficial even though the alloying element reacts with the reinforcing fiber.

The results obtained agree qualitatively with those predicted from the theoretical analyses of the mechanical behavior of discontinuous-fiber-reinforced composites reported in references 1, 4, 6, and 7. A review of the theoretical analyses is presented in the appendix. Only limited data, however, have been obtained to substantiate the theoretical analysis, particularly at elevated temperature; therefore, the results of this investigation will be quantitatively compared with those predicted.

Kelly and Tyson (ref. 4) and Spencer (ref. 6) have derived similar equations that relate discontinuous-fiber-reinforced composite strength with the length of the fiber in the composites. Kelly and Tyson's equation is as follows:

$$\sigma_C = \sigma_m^*(1 - V_f) + \sigma_f\left(1 - \frac{L_c/D}{2L/D}\right)V_f \tag{1}$$

where

σ_C composite tensile strength for fibers assumed to be alined parallel to tensile axis of specimen

σ_m^* stress on matrix at strain where fiber reaches its ultimate tensile strength

V_f volume fraction occupied by fiber

σ_f ultimate tensile strength of fiber

L_c/D critical length-diameter ratio of fiber necessary to stress fiber to its ultimate tensile strength

L/D length-diameter ratio of fibers in composite

The preceding equation is valid for values of L/D equal to or greater than L_c/D. An approximate value for L_c/D can be obtained from the following equation:

$$\frac{L_c}{D} = \frac{\sigma_f}{2\tau} \tag{2}$$

where τ is the shear strength of the matrix or the interface.

The results obtained for composites containing fibers alined parallel to the axis of the test specimens agree qualitatively with those predicted in equation (1) since, as the length of the discontinuous fibers decreased, the tensile strength of the composites decreased.

The value of L_c/D at the test temperatures investigated must be determined in order to compare quantitatively the results obtained with those predicted by equation (1). The value of L_c/D could be determined from equation (2) if the proper value for the shear strength of the matrix were known; however, it is not obvious what value for the shear strength is appropriate for a work-hardenable matrix such as copper. For example, Kelly and Tyson (ref. 4) evaluated L_c/D by embedding one end of a fiber in the matrix and applying a load through the free end. The shear strength of the matrix was then calculated from equation (2). However, this value for the shear strength of the matrix was appreciably larger than that calculated from tensile result data for composites since the degree of the matrix work-hardening which took place in the composite was not as great. In view of this, the critical aspect ratio L_c/D for the composites tested was calculated from tensile ~~result~~ data obtained for the composites which failed in tension. The critical aspect ratio can be obtained by plotting composite strength as a function of fiber content data for various L/D values, finding the slope of each curve for particular L/D specimens, and plotting this slope as a function of the reciprocal of the aspect ratio. Differentiating equation (1) results in

$$\frac{d\sigma_C}{dV_f} = \sigma_f - \sigma_m^* - \frac{\sigma_f/2(L_c/D)}{L/D} \tag{3}$$

where $d\sigma_C/dV_f$ is the slope of the curves of the composite tensile strength against fiber content for a specified aspect ratio L/D.

If $d\sigma_C/dV_f$ is plotted as a function of $1/(L/D)$, a linear relation should be obtained for values of L/D greater than the critical L/D. The slope of the curves in the linear region is equal to $(\sigma_f/2)(L_c/D)$. Thus, the critical aspect ratio L_c/D can be determined since σ_f is known. Plots of $d\sigma_C/dV_f$ against $1/(L/D)$ for the copper- and copper-chromium-matrix composites are shown in figures 6 and 7. From the slopes of the curves in figures 6 and 7, the obtained values of L_c/D are given in table III. Values for the shear strength of copper and the copper-chromium alloy used in this investigation were determined from equation (2). These values are also given in table III together with those of the measured ultimate tensile strength of the materials. The calculated shear strengths obtained are approximately one-half the ultimate tensile strength of the matrix materials. Kelly and Tyson found the same relation between the shear strength and the ultimate tensile strength for unalloyed-copper - tungsten-fiber composites (ref. 4).

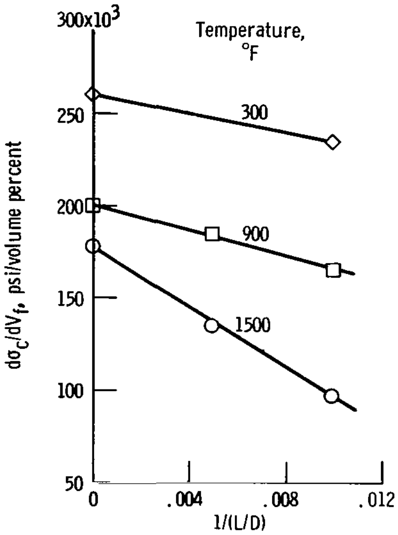


Figure 6. - Determination of critical aspect ratio from composite data for tungsten-fiber - copper-matrix composites.

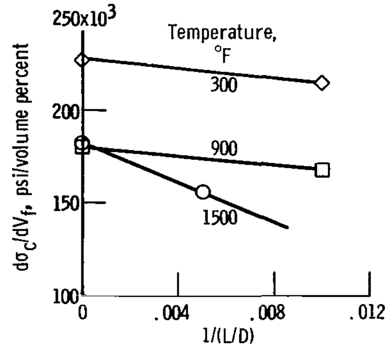


Figure 7. - Determination of critical aspect ratio from composite data for tungsten-fiber - copper - 2-percent-chromium-matrix composites.

TABLE III. - CRITICAL ASPECT RATIO AND SHEAR STRENGTH AS FUNCTION OF TEMPERATURE

Temperature, °F	Calculated critical length-diameter ratio, L_c/D	Calculated shear strength, psi	Ultimate tensile strength, psi
Copper matrix			
300	19.2	7 100	13 500
900	34.1	3 000	6 300
1500	92.2	980	2 000
Copper - 2-percent-chromium matrix			
300	9.7	12 700	24 500
900	13.5	7 200	12 300
1500	55.9	1 650	3 500

Thus, the load transfer capability of the copper-chromium alloy, indicated by the smaller critical aspect ratio L_c/D, is much greater than that for the copper matrix since the shear strength of the copper-chromium alloy is greater and the fiber itself is slightly weaker. The greater load transfer capability of the copper-chromium matrix permits higher average fiber stresses, which result in higher composite strengths than those observed for copper-matrix composites.

The values shown in table III indicate that composites consisting of a copper-chromium matrix and having fibers with length-diameter ratios less than 56 at a test temperature of 1500° F should fail by fiber pullout. Data for copper-chromium composites, tested at 1500° F and containing fibers with a length-diameter ratio of 50, are plotted in figure 2 (p. 7). If the fibers contained in a discontinuous-fiber-reinforced composite are less than L_c, the fibers will pull out before they reach their ultimate tensile strength because of matrix shearing at the matrix-fiber interface. As proposed in references 4 and 6, when this occurs, the predicted composite tensile strength (for axially oriented fibers) is expressed as

$$\sigma_C = \sigma_u(1 - V_f) + \tau \frac{L}{D} V_f \tag{4}$$

where σ_u is the ultimate tensile strength of the matrix.

The tensile strengths obtained for copper-chromium composites having fibers with length-diameter ratios less than L_c/D were less than those predicted by equations (4); yet, fiber pullout did not occur. Shear failures occurred because of fiber misaline~~ment~~ which resulted in lower tensile strengths for the composites than those predicted with the assumption of axially oriented fibers.

See errata

For the investigated composites, loss of tensile strength from misalinement of fibers is explained by considering the composite stress in relation to the misalinement angle. Stowell and Liu (ref. 11) and Kelly and Tyson (ref. 4) used equations representing composite strength as a function of fiber alinement and type of failure. They assumed a model in which the volume fiber content for misalinement fiber composites changes compared with the axially alined fiber composites. This changing fiber content introduces an additional variable. If a more practical model is assumed in which volume fiber content is not changed with fiber misalinement, similar equations can be obtained. Equations resulting from the former model (refs. 4 and 11) predict an increase in composite strength for small angles of fiber misalinement in which tensile failure of the fibers occurs. When the latter model is used, the equation for tensile failure of fibers predicts no change in composite strength as a function of fiber misalinement. Equations for the other two failure modes are the same for both models. The following equations represent the composite strength for a constant volume fiber content model as it relates to misalinement angles and types of failures which could occur.

Tensile failure of the fiber:

$$\sigma_C = \sigma \tag{5}$$

Matrix or interfacial shear:

$$\tau = \sigma \sin \Phi \cos \Phi \tag{6}$$

Tensile failure of the matrix:

$$\sigma_u = \sigma \sin^2 \Phi \tag{7}$$

where

σ_C composite tensile strength (assuming axially alined fibers)

σ applied stress on composite

Φ angle between fiber and tensile axis of specimen

τ shear strength of matrix or of interface

σ_u ultimate tensile strength of matrix in plane strain

The failure mode of the composite is determined by the lowest stress condition which satisfies any of equations (5) to (7).

From equations (5) to (7), the tensile strength of a discontinuous-tungsten-fiber-reinforced copper composite was calculated as a function of fiber orientation and is plotted in figure 8. A 30-volume-percent fiber content was used in the calculation at a test temperature of 1500° F. The plot also shows the failure modes that would be expected for different orientations of the fibers in the composite. For a small misalinement of the fibers from the axial direction, the matrix between the fibers is strong enough to support a shear load capable of fracturing the fibers in tension. Further misorientation leads to shear failure of the matrix, which is indicated by the drop in the curve with increasing misorientation. At 45°, the resolved shear stress would be a maximum and the composite stress would be a minimum. As the angle is increased above 45°, there is a tendency to stress the matrix alone in tension

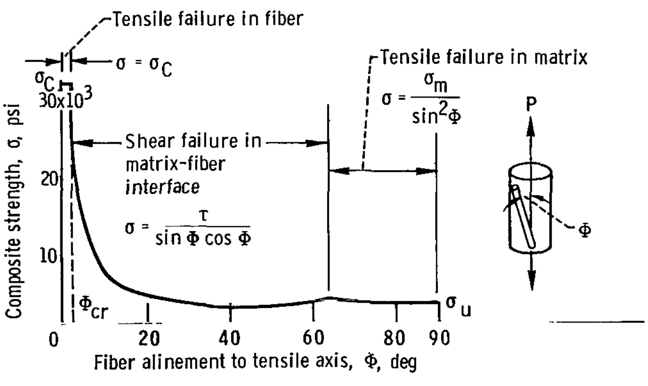


Figure 8. - Composite strength as function of fiber alinement to tensile axis.

rather than in shear, which would cause tensile failure of the matrix. It should be noted that equations (5) to (7) did not take into account the possibility of fiber rotation towards the test axis during deformation, the results of which are a reduction of the angle of misalinement and changes in composite strength. Increased values for the shear strength of the matrix can occur when the interfiber spacing is small. If both factors are considered and do operate, the curve shown in figure 8 would shift to the right. Also, the plotted curves indicate that there is a critical angle beyond which shear of the matrix occurs. The critical angle can be determined by equating the stress necessary to cause failure of the fiber (eq. (5)) with that necessary to cause shear of the matrix (eq. (6)), as shown in the following equation:

$$\Phi_{cr} = \frac{1}{2} \arc \sin \frac{2\tau}{\sigma_C} \qquad (8)$$

The critical angle of misalinement is lowered as the volume fraction of fiber is increased, since the composite tensile strength σ_C increases with increasing volume-percent fiber content. The ratio of the shear strength of the composite is lowered with increasing fiber content, and a lower critical angle results. The greater the volume percent fiber content, the smaller the value of the critical angle. Figure 9 shows a plot of composite strength against the critical angle for copper-tungsten composites calculated for a test temperature of 1500° F by using equation (8) and composite tensile data. As indicated from figure 9, the angle of misalinement must be limited to very small values in order to achieve high composite strength. In figure 10, composite tensile strength is plotted as a function of fiber length and orientation for tungsten-fiber - copper composites tested at 1500° F. The linear curves plotted for composites containing fibers with length-diameter ratios of 100, 200, and 300 are for fibers that are alined parallel to the tensile axis of the specimen. Curves of composite strength as a function of fiber content are also plotted for specimens containing fibers alined at specific angle to the tensile axis. If, for example, the fibers are alined 3° from the tensile

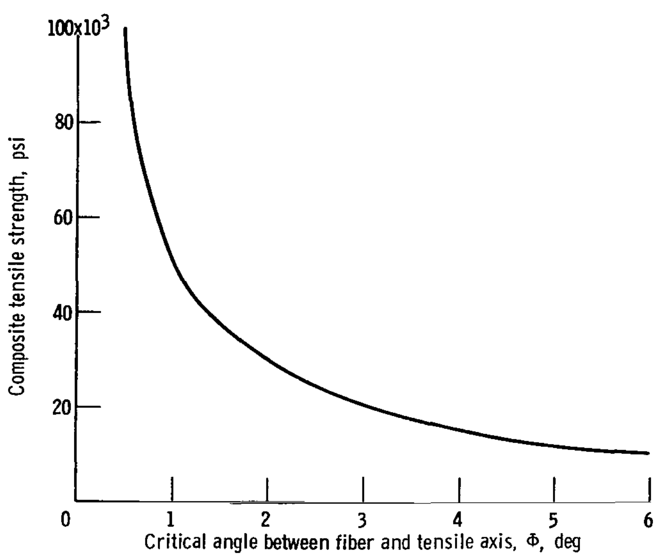


Figure 9. - Composite tensile strength as function of critical angle for tungsten-fiber - copper-matrix composites at 1500° F.

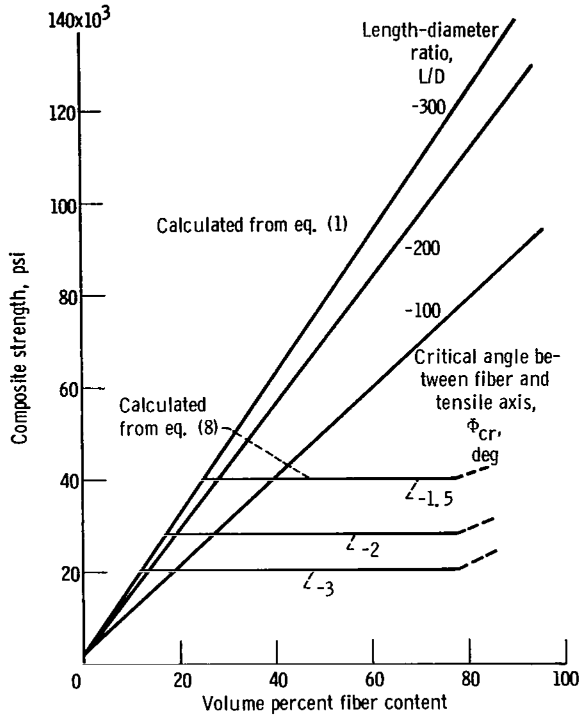


Figure 10. - Composite strength as function of fiber length and orientation for tungsten-fiber - copper-matrix composites at 1500° F.

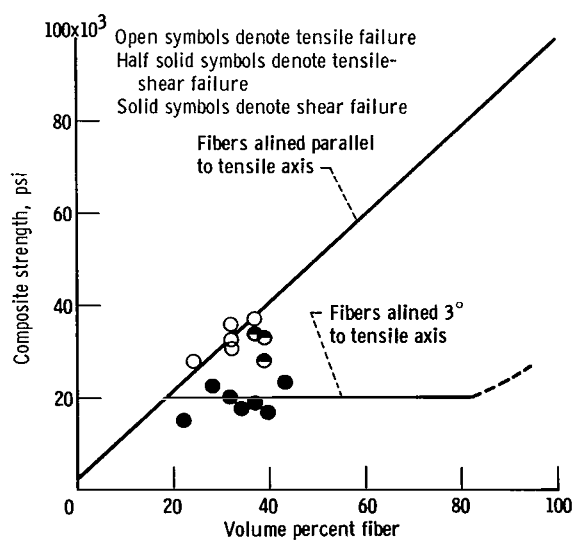
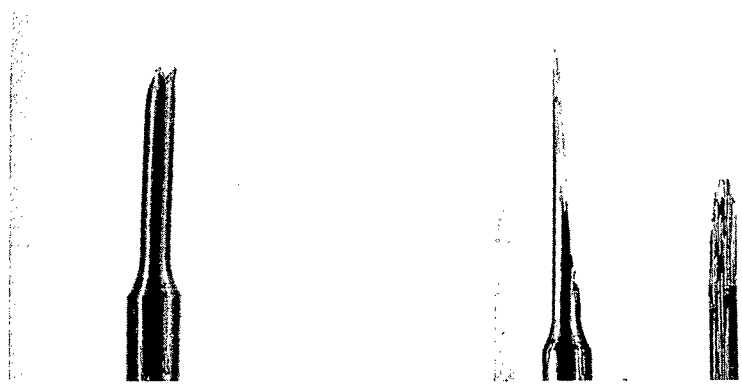


Figure 11. - Composite strength as function of fiber content and orientation for tungsten-fiber - copper-matrix composites with length-diameter ratio of 100 at 1500° F.

axis, shear failures occur for composites containing 12 or more volume percent fibers that have a length-diameter ratio of 300. (This is the critical angle of misalinement calculated from eq. (8).) For specimens containing fibers with a length-diameter ratio of 100, the volume-percent fiber content necessary for shear failure to occur is approximately 19. Thus, with a constant angle of misalinement, the volume-percent fiber content of the composite necessary to cause shear failures is decreased with an increasing length-diameter ratio of the fibers in the composite. With a constant volume-percent fiber content, the critical angle of misalinement decreases with increasing length-diameter ratio of the fibers in the composite. The curve of the composite strength against volume-percent fiber, for composites containing fibers alined at an angle to the tensile axis so that shear failure of the matrix can occur at a specific volume fiber content, would be expected to obey the law of mixtures equation (eq. (1)) up to the volume-percent fiber content where matrix shear occurs because of fiber misalinement. Above this fiber content, the composite strength would be expected to be independent of fiber content and to remain constant up to very high fiber contents, as shown in figure 10, where exceptional work-hardening of the matrix may occur as a result of very close packing of the fibers with accompanying overlapped strain fields. The actual data obtained for copper - tungsten-fiber composites at a test temperature of 1500° F are compared with the expected behavior as a function of orientation of the fibers in figure 11. The curve of σ_c against V_f

shown in figure 11 is the curve predicted from the law of mixtures equation, which assumes that the fibers are oriented parallel to the tensile axis of the specimen. It is mentioned earlier that specimens that contained fibers oriented less than 2° from the tensile axis failed in tension. The plot in figure 11 shows that these materials had tensile strengths which were in agreement with those predicted from the law of mixtures equation. Specimens in which only a portion of the fibers were alined parallel to the tensile axis had tensile-shear failures and had lower tensile strengths than those predicted, as shown in figure 11. All the specimens that failed in shear had fibers alined approximately 3° to 4° from the tensile axis of the specimen. These values of fiber alinement agree very well with the calculated critical angle of alinement for a tungsten-fiber-copper composite tested at 1500° F and containing approximately 20 volume percent fibers with a length-diameter ratio of 100. Below this fiber content, the composite is expected to fail in tension; the plot of composite strength against fiber content obeys the law of mixtures equation. Above this fiber content, the composite fails in shear and the strength of the composite would be expected to be nearly constant up to very high fiber contents. Thus, the data obtained in this investigation appear to agree with the curve of composite strength against fiber content predicted for composites containing fibers alined 3° from the tensile axis, as shown in figure 11.

Metallographic examination of the fractures and necking of the fibers also tends to corroborate the validity of the previously discussed failure mode. Examples of two types of fractures observed are shown in figure 12. Specimens having fibers alined parallel to the tensile axis failed in tension, and necking of the fibers occurred, which indicated fiber failure. Specimens having fibers alined at an angle to the tensile axis failed in shear on the plane and also at the angle at which the fibers were oriented to the tensile axis, as shown in figure 12. Fiber necking generally was not observed: specimens in which some of the fibers were alined parallel to the tensile axis had necked fibers (those which were alined), but the misalined fibers did not neck.



(a) Tensile failure (alined fibers).

(b) Sheer failure (misalined fibers).

Figure 12. - Effect of fiber alinement on failure mode.

There is great interest in composites for use at temperatures beyond the current use range of nickel- or cobalt-base superalloys, which at present is limited to temperatures below 1800° F. Alumina-whisker-reinforced nickel-base composites appear promising. The length-diameter ratio of such whiskers should be sufficient to cause failure of the whisker to occur and to reinforce the nickel-base alloy successfully. The results of this investigation, however, indicate that fiber alinement might be a serious problem to overcome. Consider a hypothetical case, the reinforcement of MAR M 200, currently one of the strongest investment-cast nickel-base alloys, with 50 volume percent whiskers. At 2000° F the critical angle of alinement is calculated to be 3°. With 25-volume-percent-whisker reinforcement, the critical angle of alinement is approximately 5°. Thus, excellent alinement is needed to reinforce nickel-base alloys successfully. These values are for one of the strongest alloys available, and the allowable misalinement would be greater than for weaker, more conventional alloys. The alinement may be further complicated by the short length of the whiskers, since the ability to orient the whiskers may be controlled more by total length than by length-diameter ratio. While length-diameter ratios of 100 to 200 are very high for the very small diameter whiskers or whisker wool (typically approx. 0.00015-in. diam), the length is only 0.1 to 0.3 inch and great care must be taken to effect good alinement. Of course, increased length of the fibers could aid alinement; thus, an alleviation of the potential difficulty would be to modify whisker growth to increase length.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the metallurgical and geometrical factors affecting elevated-temperature tensile properties of discontinuous-tunsten-fiber-reinforced composites:

1. The fiber orientation in the composite was extremely critical at elevated temperatures. Shear failures occurred for specimens tested at 1500° F in which the fibers were misalined from the tensile axis by as little as 3°. Composites that failed in shear had significantly lower tensile strengths than did composites having fibers alined parallel to the tensile axis of the specimen. The critical angle of alinement beyond which shear of the composite occurs on a plane parallel to the fiber orientation was in agreement with predicted values.

2. Tensile strengths of discontinuous-fiber-reinforced composites with fibers alined parallel to the tensile axis were dependent upon the length-diameter ratio of the fibers. As the length-diameter ratio of the reinforcing fibers decreased, the tensile strengths of the composites decreased. Values obtained agreed with those predicted.

3. Load transfer from the matrix to the fiber was dependent upon the shear strength

of the matrix. The greater the shear strength, the higher the load transfer capabilities of the matrix.

4. Alloying the matrix was beneficial even though the alloying element reacted with the fiber. The chromium addition to copper increased the shear strength of the matrix. The ability of the copper alloy to transfer load was greater than that of the unalloyed copper. The ability of the copper alloy to transfer greater loads with the same length-diameter ratio of the fiber resulted in higher strength composites. Alloying the matrix to increase its shear strength also allowed for greater tolerance in the misalinement of the reinforcing fibers.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 12, 1966,
129-03-09-01-22.

APPENDIX - REVIEW OF THEORETICAL ANALYSES OF MECHANICAL BEHAVIOR OF DISCONTINUOUS-FIBER-REINFORCED COMPOSITES

The information presented is a review of the theoretical analyses of the mechanical behavior of discontinuous-fiber-reinforced composites which have been reported in references 1, 4, 6, and 7. Most of the investigations of the mechanical behavior of discontinuous-fiber-reinforced composites assume that the fibers in the composite are of equal length and diameter, are uniformly distributed throughout the composite, and are alined parallel to the tensile axis. A further assumption is that a good bond exists between the fiber and the matrix and that the fibers overlap one another lengthwise in the manner shown in figure 13. Uniform overlap implies that no two fibers are at the same longitudinal position and that the distance from the leading end of one fiber to the fiber whose longitudinal position is closest to that of the first fiber is the same for all the fibers in the composite. Uniform overlap would be approached if a large number of alined fibers were distributed randomly throughout the specimen. Short fibers must be overlapped a certain minimum distance, or fiber pull out will occur before the reinforcing fibers reach their ultimate tensile strengths.

When a composite containing uniaxially oriented fibers is stressed in a direction parallel to the longitudinal axis of the fibers, axial stresses in the fiber and the matrix are different as a result of the difference in elastic moduli of the components. Shear stresses are produced in planes parallel to the tensile axis of the fiber and in the direction of the axis of the fiber; these stresses restrict the matrix from freely elongating in the region of the fiber. Interfacial shear is thus assumed to be the basic means of load transmission from the matrix to the fiber. Direct transmission through the ends of the fiber by tension is neglected since the matrix material is in general much weaker than the reinforcing fiber. The ends of the fiber are thus assumed to be unstressed, as shown in figure 14. The tensile stresses in the fiber vary along its length in the vicinity of the ends, and the shearing strains in the matrix and around the interface will tend to rise sharply near the ends of the fiber, as shown in figure 14 and confirmed in reference 10. If the fibers are packed close together, these strain regions will overlap,

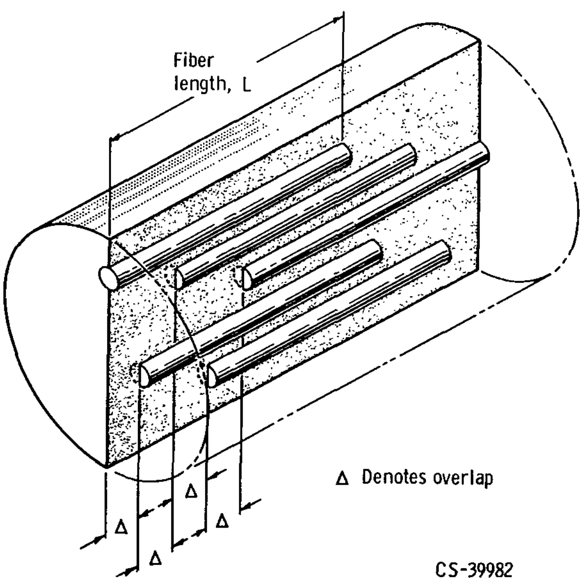


Figure 13. - Schematic drawing of discontinuous fiber composite showing uniform overlap of fibers.

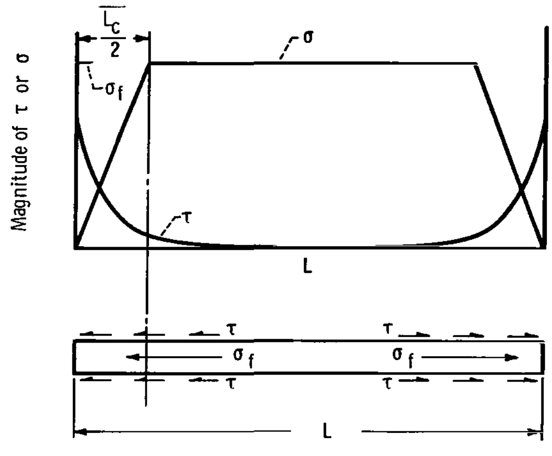
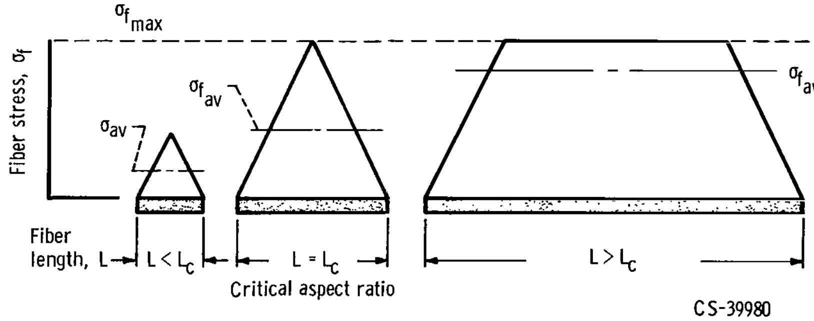


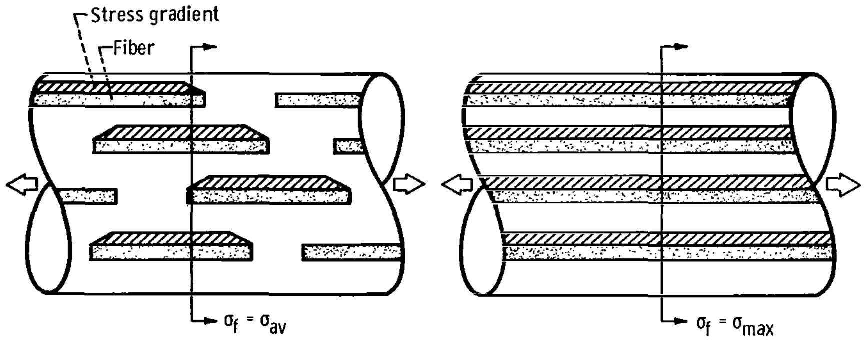
Figure 14. - Stress distribution within and on surface of fiber.

so that strain hardening of the matrix is likely to contribute to the strength of the composite. The strain in the matrix will also be altered by differences in Poisson's ratio and differences in coefficient of thermal expansion between the fiber and the matrix. The end portion of the fiber in which the tensile stress varies is referred to as the critical length or ineffective length. Beyond this critical length the fiber can be stressed to its maximum value, which is equal to the ultimate tensile strength of the fiber. The stress beyond the critical length remains constant, as shown in figure 14. It is also assumed that the stress gradient at the end of each is linear within the ineffective or critical length. Thus, there is a specific length of fiber necessary to stress the fiber to its ultimate tensile strength, which is equal to the critical length L_c. If the fiber length is less than L_c, the fiber will not be stressed to its ultimate tensile strength, as shown in figure 15. It can also be seen from figure 15 that, as the fiber length is increased above L_c, the portion of the fiber stressed to its maximum value increases. The average stress on the fiber thus increases as the length of fiber increases. Since the fibers are the prime contributors to the strength of a fiber-reinforced material,



$$\sigma_{f_{av}} = \sigma_{f_{max}}\left(1 - \frac{L_c}{2L}\right)$$

Figure 15. - Fiber stress distribution. (Tensile stress gradient on fiber as function of length.)



(a) Discontinuous fibers; $\sigma_C = \sigma_m^*(1 - V_f) + \sigma_{f_{max}}(1 - L_C/2L)V_f$, where $L_C = \sigma_{f_{max}} D_f/2\tau$.

(b) Continuous fibers; $\sigma_C = \sigma_m^*(1 - V_f) + \sigma_{f_{max}} V_f$.

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Figure 16. - Comparison of fiber stress contributions.

two major factors become important to the strength of the composite material: the critical length L_c and the ratio of L_c to the total fiber length L. Fibers having a length less than L_c will pull out of the matrix before the fiber reaches its ultimate tensile strength. The importance of the ratio of L_c to L can be best illustrated by comparing a discontinuous-fiber-reinforced composite to a composite reinforced with continuous-length fibers (fig. 16). In a continuous-fiber-reinforced composite, the composite reaches its ultimate tensile strength in a plane where the fibers have been stressed to their maximum value. In a discontinuous-fiber composite, however, the ultimate tensile strength of the composite is reached in a plane where the stress level on the fibers is not the ultimate strength of the fibers but rather a lower stress level. The longer the fiber, the lower the number of points of discontinuity or the number of fibers in any given cross section that have not been stressed to their ultimate tensile strength. The smaller the ratio of the critical length to the total length of the fiber in the discontinuous-fiber-reinforced composite, the closer it approaches the tensile strength of a continuous-fiber-reinforced composite.

Kelly and Tyson (ref. 4) have derived a relation between the ratio of L_c to L and the average fiber stress, which can be expressed as

$$\overline{\sigma}_f = \sigma_f\left(\frac{1 - L_c}{2L}\right) \quad \text{See errata.} \tag{A1}$$

where $\overline{\sigma}_f$ is the average fiber stress and σ_f is the ultimate tensile strength of the fiber. Composites containing continuous-length fibers are assumed to have infinite-length fibers whose average fiber stress is the ultimate tensile strength of the fiber. The longer the fibers contained in a discontinuous-fiber-reinforced composite, the nearer it approaches

the tensile strength of a continuous-fiber-reinforced composite.

Studies of McDanels, Jech, and Weeton (ref. 1) have shown that the tensile strengths obtained for both continuous- and discontinuous-fiber-reinforced composites were equal within experimental error. Their investigation of copper reinforced with parallel fibers of tungsten demonstrated that the composite strength was a linear function of the fiber content and of the ultimate tensile strength of the tungsten fibers, which is

$$\sigma_C = \sigma_m^* V_m + \sigma_f V_f \tag{A2}$$

where

σ_C	ultimate tensile strength of composite
σ_m^*	stress on matrix at strain where fiber reaches its ultimate tensile strength
V_m	volume fraction occupied by matrix
σ_f	ultimate tensile strength of fiber
V_f	volume fraction occupied by fiber

Later, Cratchley (ref. 9) and Kelly and Tyson (ref. 4) confirmed this linear relation.

The average ultimate tensile strength of the fibers when tested individually was the same as that attained by the embedded fibers for both continuous- and discontinuous-fiber-reinforced composites tested, since their ratio of L_c to L was high (ref. 1). The fibers were long enough to have a large ratio of length to critical length so that the average tensile stress on each fiber approached that of continuous-length fibers, as indicated in figure 15. However, as pointed out by Kelly and Tyson (ref. 4), and Spencer (ref. 6), discontinuous-fiber-reinforced composites should always have strengths lower than continuous-fiber-reinforced composites since the average fiber stress decreases with decreasing fiber length. Substitution of equation (A1) for the fiber stress in equation (A2) thus gives the equation

$$\sigma_C = \sigma_m^*(1 - V_f) + \sigma_f\left(\frac{1 - L_c}{2L}\right)V_f \tag{A3}$$

Equation (A3) is valid for values of L equal to or greater than L_c. An approximate value for L_c can be obtained by equating the value of the tensile load to that of the shear load at the fiber-matrix interface and by considering that the fiber is loaded from both ends as follows:

$$L_c = \frac{\sigma_f D_f}{2\tau} \tag{A4}$$

where D_f is the diameter of the fiber.

This equation does not take into account variations of L_c with stress level, stress concentrations in fibers adjacent to failure areas, or the initial state of stress.

If the fibers contained in a discontinuous-fiber-reinforced composite are less than L_c, the fibers will pull out before they reach their ultimate tensile strength because of matrix shearing at the matrix-fiber interface, as proposed in reference 1. When this occurs, the predicted tensile strength of the composites, as proposed in references 4 and 6 is

$$\sigma_C = \sigma_u(1 - V_f) + \frac{\tau L}{D} V_f \tag{A5}$$

where σ_u is the ultimate tensile strength of the matrix.

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